Flowfield Characteristics of Low-Swirl Burner and Its Adaptability to Ultra-low Emission Applications

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Lean Premixed Combustion as a Passive Pollution Prevention Technology

- **Opportunity**
  - **Low NO_x due to low flame temperatures**
  - **Can meet most stringent air quality rules in California (NO_x < 10 ppm @ 3% O_2)**
- **Barriers**
  - **Flame stabilizer or holder dictates operating envelope**
  - **Combustion oscillations**
  - **Sensitivity to mixture inhomogeneity and compositions**

Issues with Conventional High-Swirl Stabilization Methods

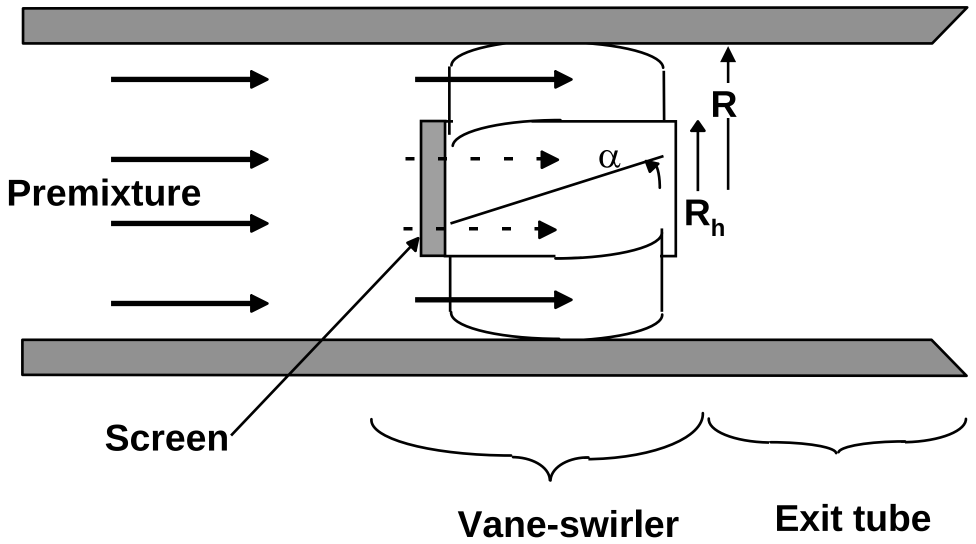
- **Dominated by strong recirculating vortex**
  - Flame stabilized by hot combustion products trapped in the vortex continuously igniting the surrounding swirling reactants
  - fragmentation of the flame fronts due to high turbulence shear stresses
  - nonlinear interactions between fluid mechanics & combustion processes coupled with vortex breakdown and precessing vortex core
- **Instabilities leading to premature blowout**
  - Onset of intermittent flame detachment precursor to blowout
- **Instabilities leading to oscillations**
  - Coupling of the flame, chamber, & recirculating swirl flow
- **Mitigation of instabilities & oscillations at ultra-lean conditions**
  - Rich/lean staging
  - Active feedback control
  - Catalytic pilot or combustor

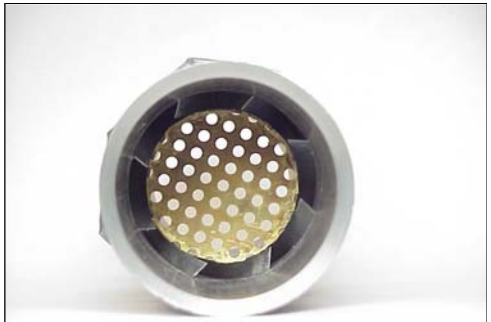
Premixed Flames Stabilized by Low Swirl

Original LSB uses air-jets to generate swirl

- **Novel concept discovered in 1991**
  - **Freely propagating lifted flame sustained by flow divergence not recirculation (patent issued 1998)**
- **Scientific Interest**
  - **Challenging problem for models and simulations**
  - **Excellent laboratory research tool**
- **Technological Interest**
  - **Capability to support ultra-lean flames**
  - **Simple design**
  - **A robust ultra-clean combustion concept rip for adaptation to many practical systems**

Vane-Swirler Developed for Practical Implementation of LSB Concept





Top view of patented vane-swirler

- Two stage air-jet LSB too elaborate for most application
- Single stage vane LSB produces the same flowfield as air-jet LSB
    - Open center channel allows a portion of flow to bypass swirl vanes
    - Angled guide vanes induce swirling motion in annulus
    - Screen balances pressure drops between swirl and centerbody
- Patent issued in 1999

Objectives of This Paper

- Present scaling rules developed for LSB
- Gain better understanding of the flowfield characteristics to explain the robust performance of LSB
  - Investigate the evolution of the flowfields of a small 2” low-swirl burner by particle image velocimetry
    - Majority our previous measurements made in the original LSB that use air jets
    - Few data sets available for the commercial LSB with a vane swirler
  - Gain some insights on flame enclosure/chamber coupling for LSB adaptation to different systems

Scaling Rules

Scaling to Industrial Sizes

- *Scientific approach for "smart" adaptation to a broad range of process heat and boiler applications*
  - **Targeting 300 KBtu/hr to 30 MMBtu/hr burners**
- *Establish scaling rules*
  - **Obtain scientific background for low-swirl flows**
  - **Comparing LSBs of different sizes (2 – 5") in furnace and boiler simulators with and without FGR (Partnering with CMC Eng., UCI, Maxon, TIAX, Zink and Aqua-Chem)**
    - **Within the operable swirl rates, vane shapes, & screen placement have secondary effects on flame noise, flame stability, & lean blow off**
    - **NO_x emissions depend primarily on air/fuel ratio**
    - **Observed maximum 30:1 turndown**

Scaling Rule 1st Step – Quantify Swirl Rates by New Derivations of Swirl Number

$$S = \frac{2}{3}\tan\alpha \frac{1 - R^3}{1 - R^2 + [m^2(1/R^2 - 1)^2]R^2}$$

- **New expression uses easily measurable parameters**
  - Ratio of center channel radius to burner radius, $R = R_c/R_b$
  - Straight or curved vane with angles, α
  - Ratio of mass flow rates through center channel and swirl annulus, m
    - Standard pressure drop procedure to obtained m from different screens

Answers to Key Scaling Questions

- What are the critical roles of LSB components on its operation?
  - **Size of center channel?** Controls back pressure
  - **Exit tube length?** Minimum length needed for proper operation
  - **Vane angle?** Flame discharge angle
  - **Vane length?** Improves turndown but can increase back pressure
  - **Screen placement position?** Upstream placement preferred
  - **Screen type?** Not critical
- How high we can push the velocities (thus power output)?
  - **Do we need to adjust swirl to accommodate flame shift?** No
  - **Will the flame blows out at high throughput?** Not observed yet
  - **How does the aerodynamic flowfield evolve at high velocities?** Self-similar
- How much can we increase the burner diameter?
  - **Will increase burner diameter affect flame stability range and thus swirl requirement?** Not observed yet
- Is there a convenient scaling rule that engineers can use? YES!

LSB Scaling Rules

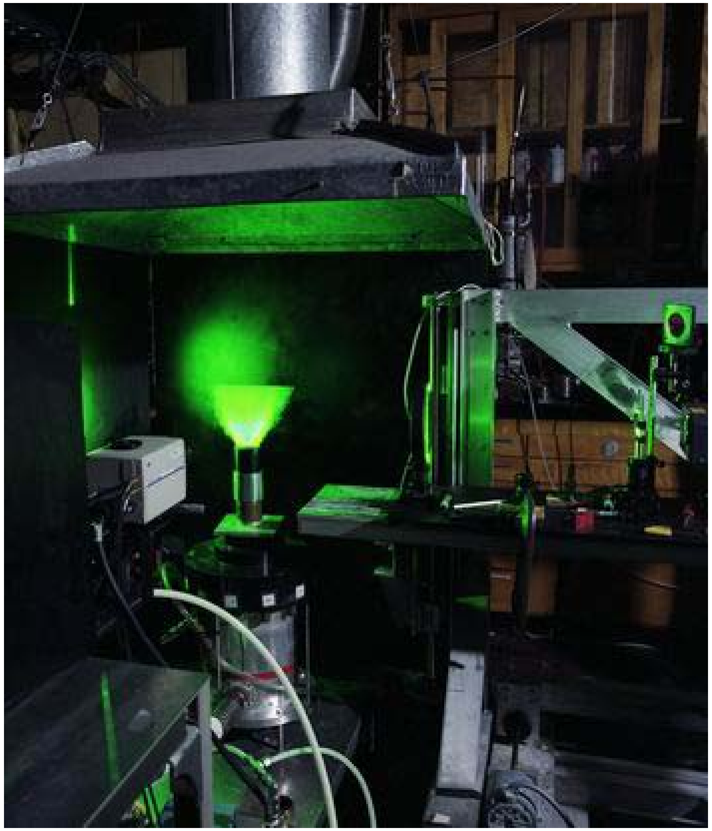
- **Keep swirl recess at 1 to 1.5 diameter**
- **Apply 0.4 < S < 0.55 criterion**
  - **Center-channel/burner ratio 0.5 < R < 0.6**
    - **Larger R increase drag thus blower power**
  - **Vane angle between 37^0 to 45^0**
    - **Vane can be curved or straight**
    - **Overlapping vanes increase turndown**
  - **Optimize burner by using different screens to change S**
    - **Screen geometry is not critical**
    - **Larger openings reduce clogging**
    - **Other options available to change *m***
- **Constant velocity scaling for power output**
  - **Output power scaled by the square of the burner diameter**
  - **Minimum operating conditions at bulk flow of 10 ft/s**
- **Optimum flame closure at 3 to 4 R_b**

PIV Studies

Burner Configuration and Experimental Conditions

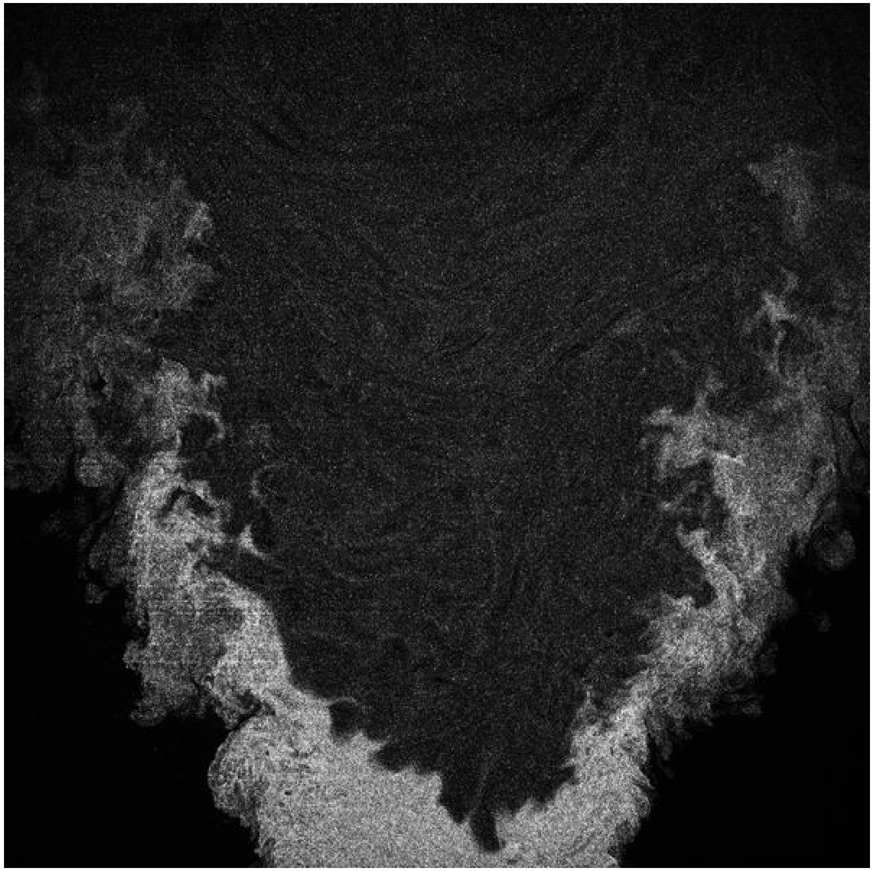
- **Equal to Maxon's smallest commercial low-swirl MPAKT-burner**
  - **R = 2.6 cm, *R* = 0.776, 8 curved vanes, α = 37° & 71% perforated plate**
  - ***m* = 0.7 and *S* = 0.53.**
- **CH_4/air mixtures supplied by cylindrical settling chamber with a converging nozzle**
- **LSB fired into ambient air without an enclosure**
- **12 sets of non-reacting and reacting PIV data**
  - **$\phi = 0$, U_0 = 5, 7.5, 10, 12.5, 15 & 17.5 m/s**
  - **$\phi = 0.7$ (5.9% O_2) U_o = 5, 10 & 15 m/s**
  - **$\phi = 0.8$ (3.9% O_2) U_o at 5, 10 & 15 m/s**
  - **28 to 83 kW (96 to 283 KBtu/hr)**

PIV System



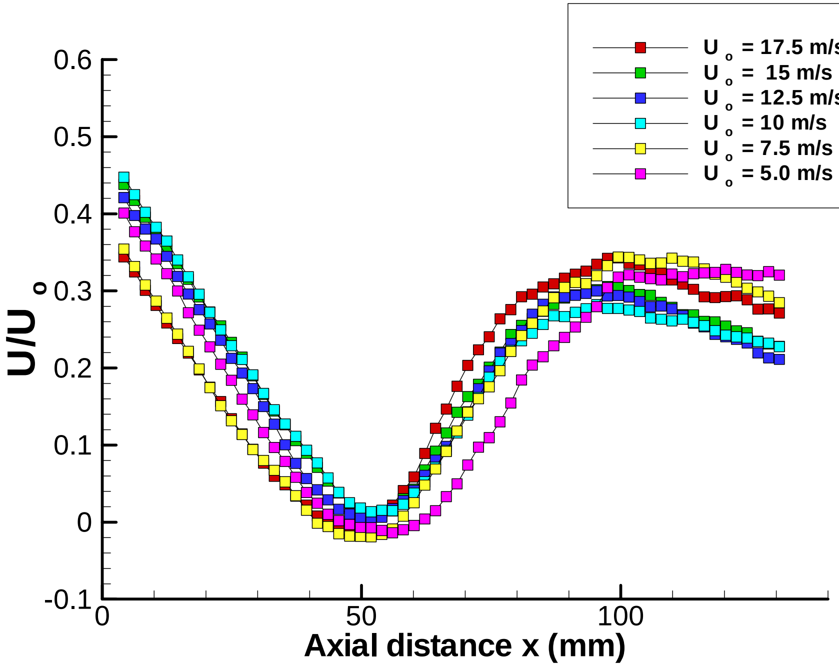
- **Acquisition**
  - **New Wave Solo PIV laser double 120 mj pulses at 532 nm**
  - **Kodak ES 4.0 2000 by 2000 pixel camera**
  - **11 by 11 cm field of view 55.62 μm/pixel**
  - **Beam thickness < 1 mm**
  - **0.3 μm Al_2O_3 particles**
  - **Time separation 35 μsec**
  - **448 image pairs**
- **Analysis**
  - **64 by 64 sub-region (3.56 mm)**
  - **-3 ε rejection criterion**

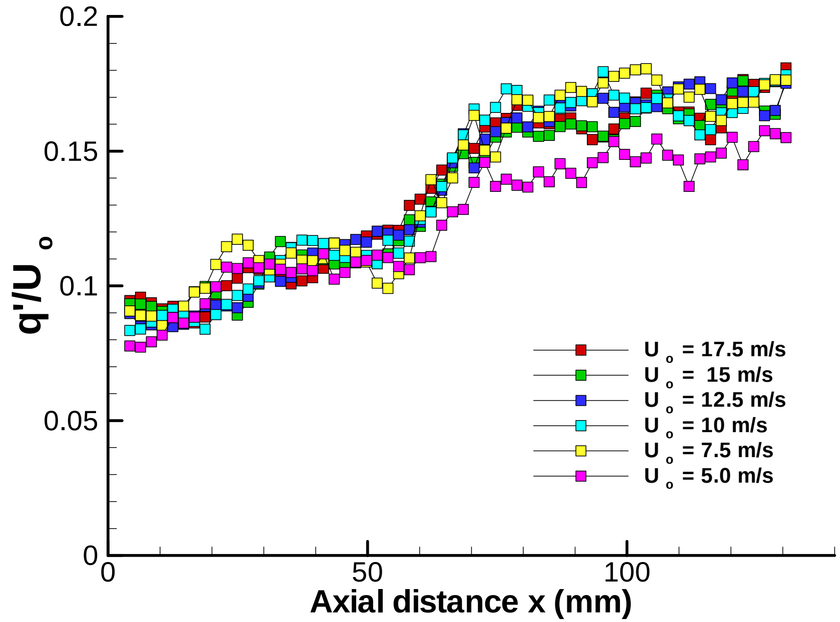
Raw PIV Image Shows Wrinkled Structures of the Lifted LSB Flame



- **Characteristic thin wrinkled structures of premixed turbulent flames are delineated by the drastic change in Mie scattering intensity across the flame fronts**
- **Wrinkle sizes consistent with integral length scale of inflow turbulence**

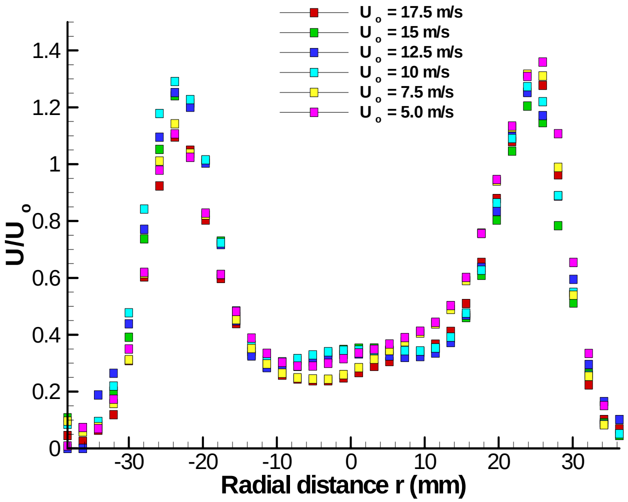
Non Reacting Centerline Profiles

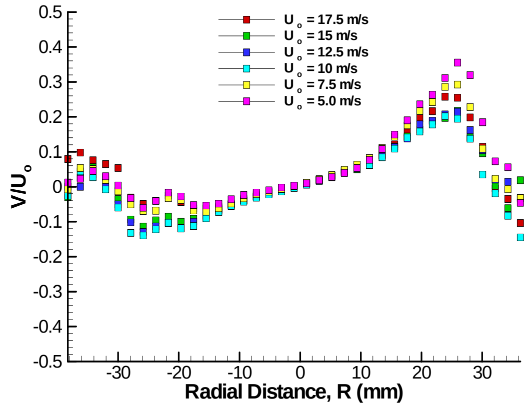


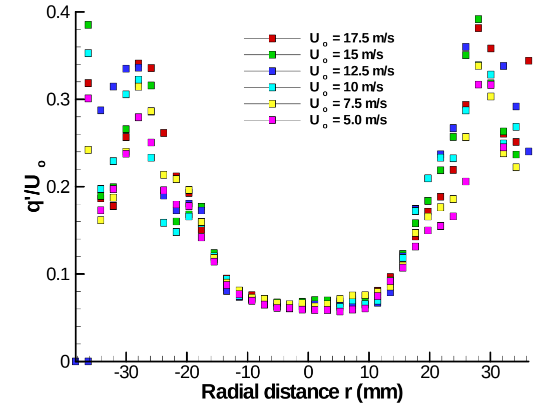


- **Normalizing centerline profiles of mean axial velocity, U, and two-component turbulent kinetic energy, q’, by bulk flow velocity U_o show self similarity of non-reacting flowfields**

Non-Reacting Radial Profiles at X = 20 mm







- **Normalizing radial profiles of mean axial velocity, U, mean radial velocity, V, and two-component turbulent kinetic energy, q', by bulk flow velocity U_o gives more evidence to the self similarity nature of the non-reacting LSB flowfields**

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Self-Similar Flowfields Explain Why No Flame-Shift During Load Change

- **Flame position, x_f and flame speed S_T satisfy equality**

$$U_o - \frac{dU}{dx}(x_f - x_o) = S_T$$

x_o is the virtual origin of the axial U/U_o profiles

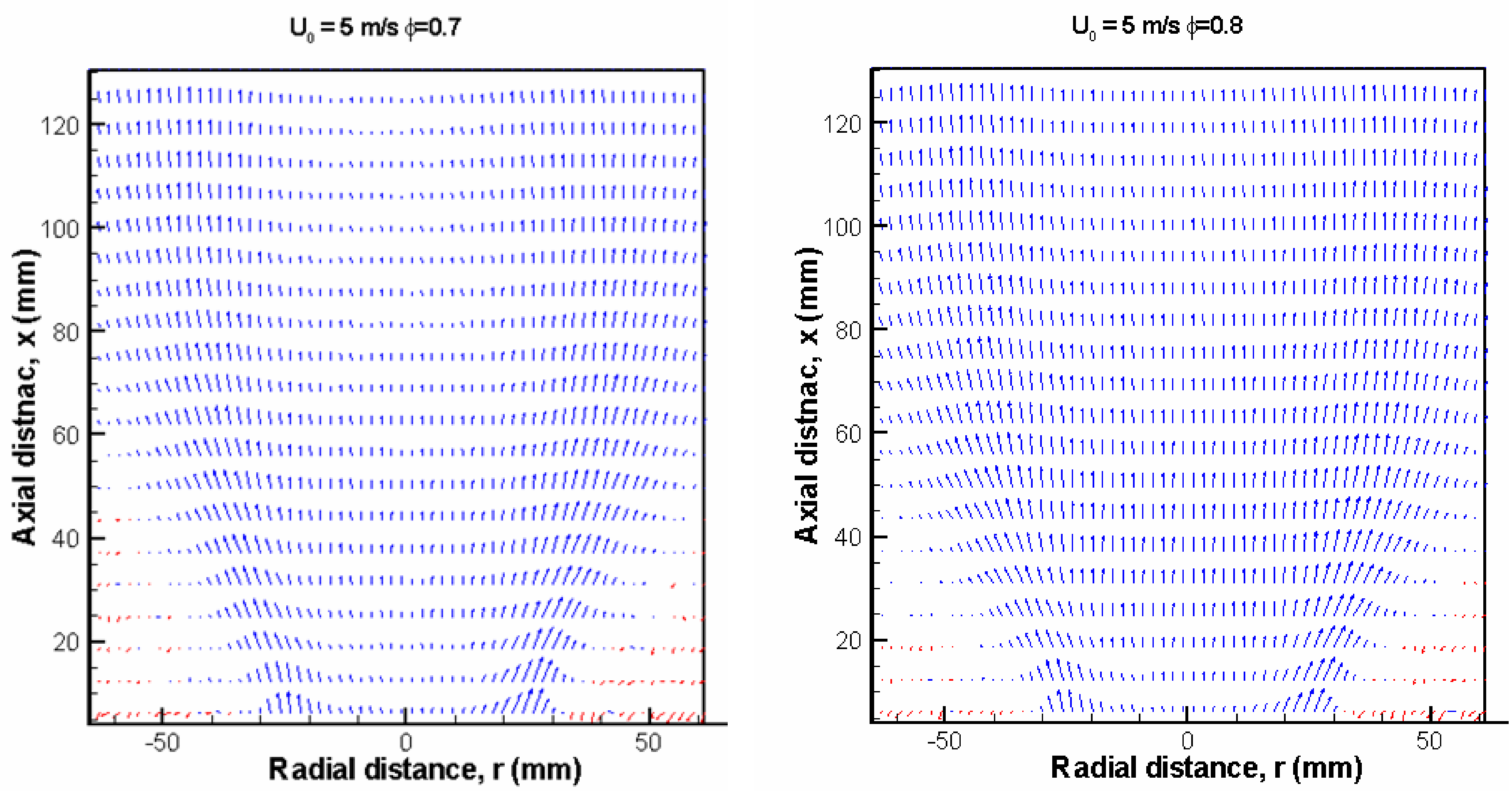
- **Dividing through by U_o and invoking linear dependency of S_T with u' render**

$$1 - \frac{dU}{dx}\frac{(x_f - x_o)}{U_o} = \frac{S_L(1 + Ku')}{U_o}$$

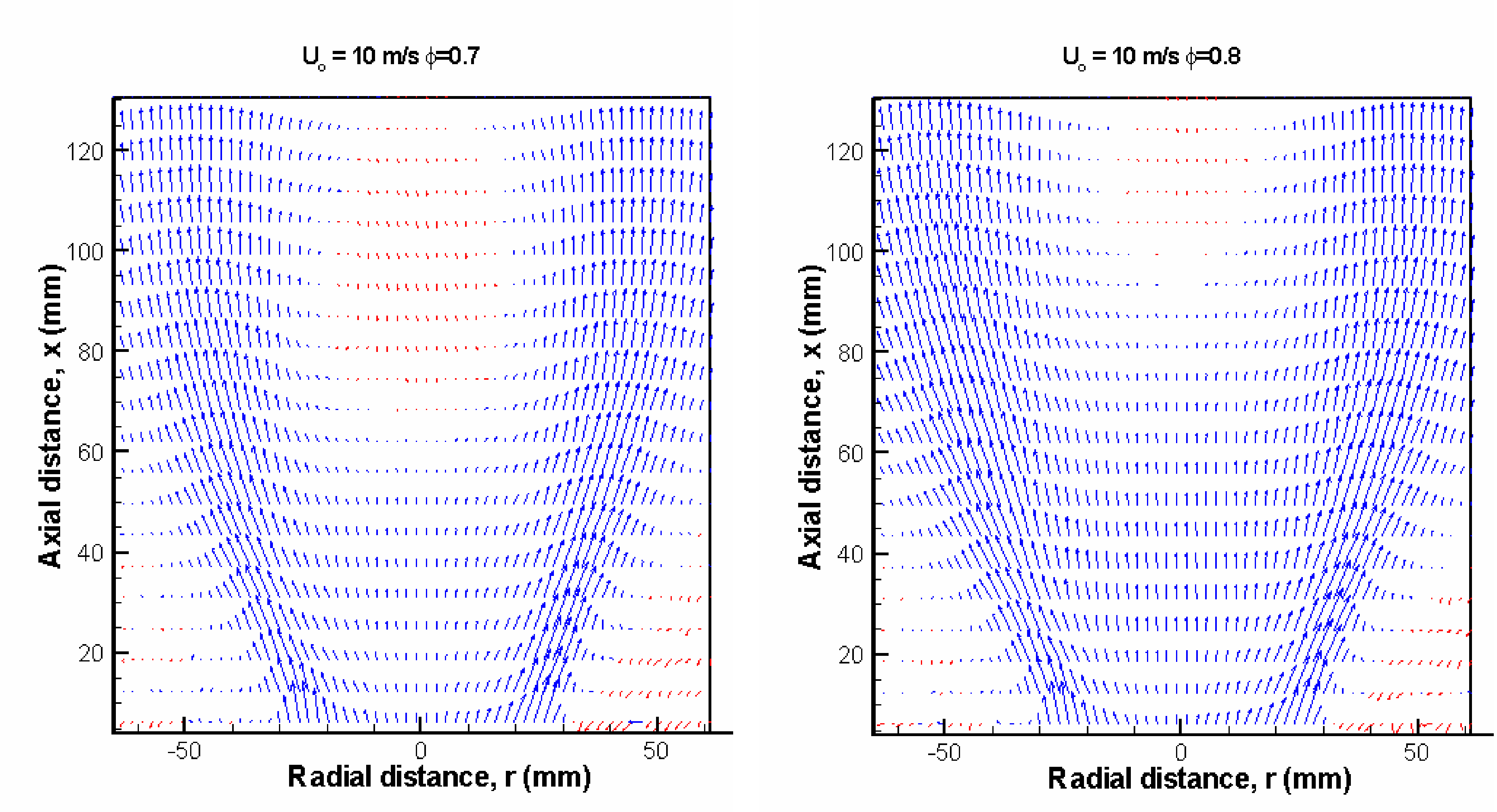
  - **S_L is the laminar flame speed with values from 0.2 to 0.5 m/s for NG**
  - **self-similarity shows that $dU/dx/U_o$ on LHS is constant ($8\ m^{-1}$)**
  - **u'/U_o on RHS tends to a constant value for large u'**

- **x_f invariant with U_o and has small dependence on ϕ through S_L**

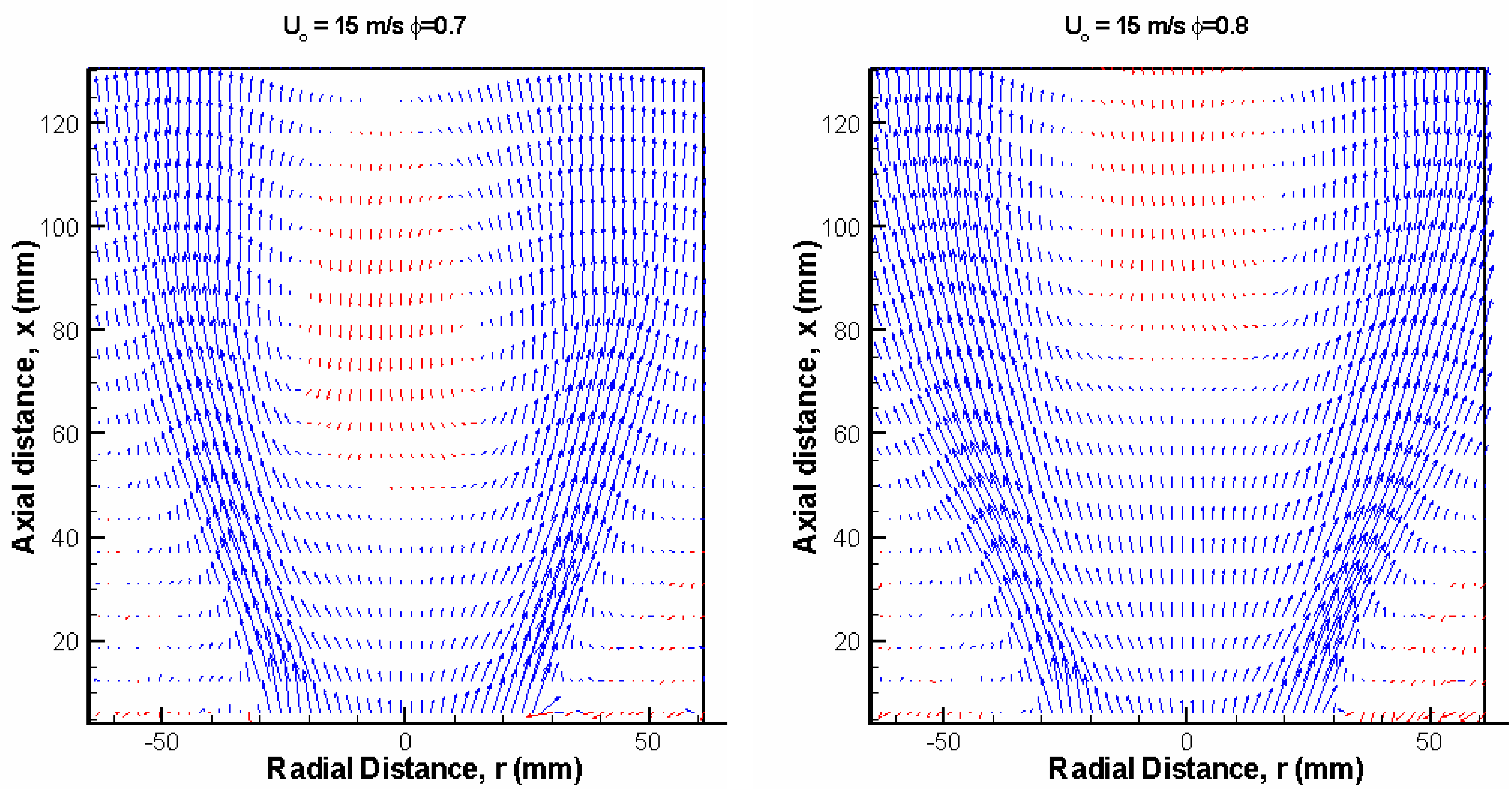
Velocity Vectors of U_o = 5 m/s Flames



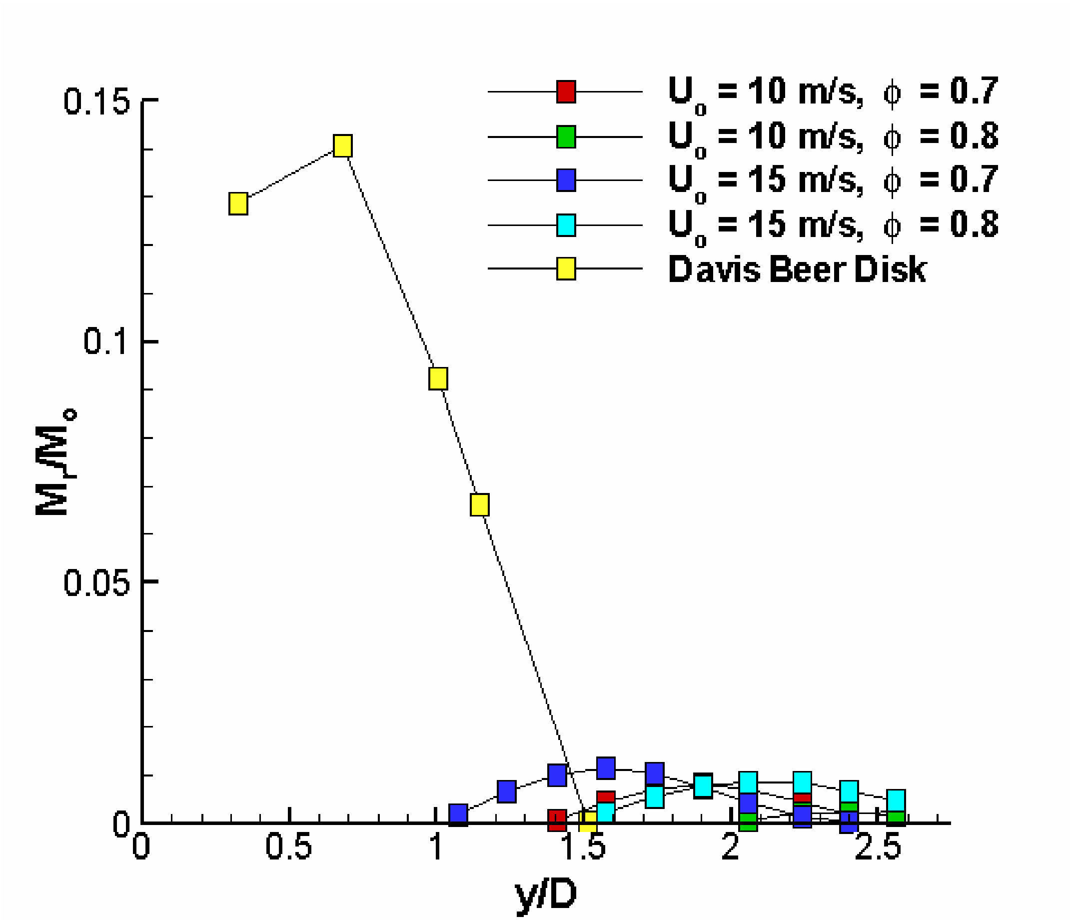
Velocity Vectors of U_o = 10 m/s Flames



Velocity Vectors of U_o = 15 m/s Flames



Quantified Recirculation Strength



- **Reversed mass flux at a give x obtained by**

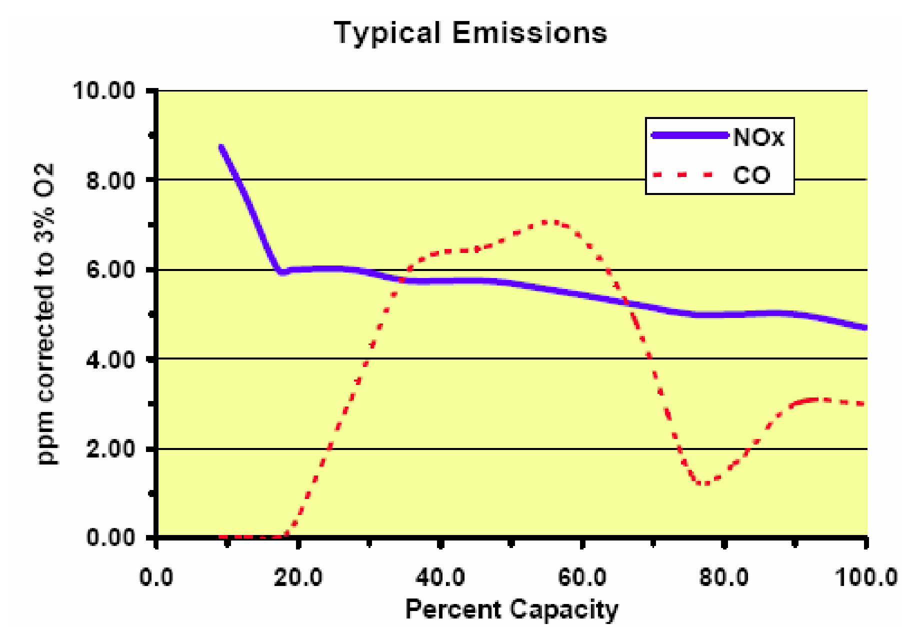
$$M_r = \int_0^{r_0} 2\pi\, r \rho U dr$$

for U < 0

- **Assumed ρ_p/ρ_r = 0.162 and 0.15 respectively for ϕ = 0.7 and 0.8**
- **M_r/M_o of LSB flames significantly lower than typical recirculation in the wake of a disk**

Commercialization for Process Heat

- **Maxon Corp. licensed LSB in 2002**
- **Target ultra-low NO_x market (< 9 ppm @ 3% O_2) for industrial heating, baking and drying**
- **First products of 1 – 6 MMBtu/hr, 10:1 turndown available since Sept. 2003**
- **55 units shipped and SCAQMD BACT certification pending**
- **Demonstrate improvement in product quality for paint curing and food processing**
- **Products up to 25 MMBtu/hr being developed targeting 20:1 turndown**

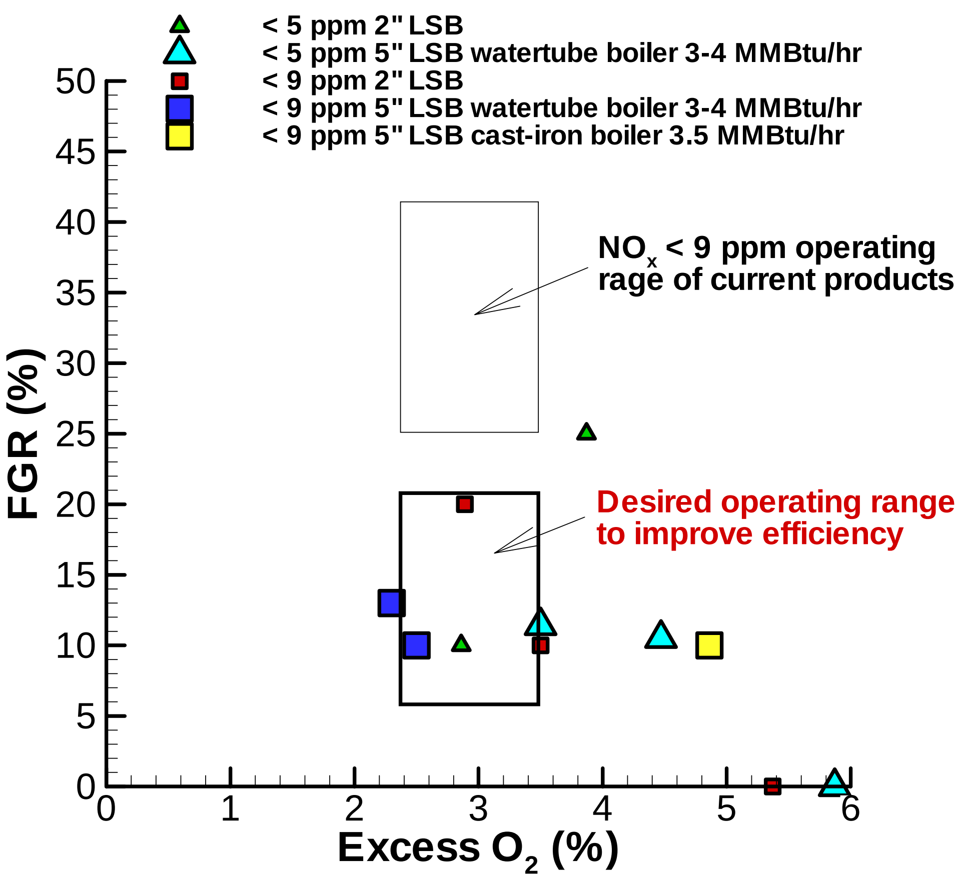


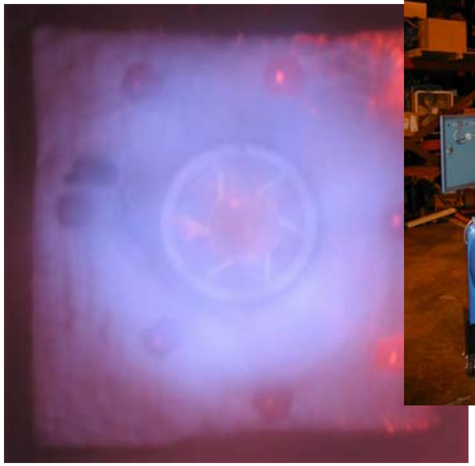
Maxon Identified Significant Economic and Technical Advantages of LSB

- Burner design scalable by governing equations
  - A radical departure from experimentation approach
- Size compatible to existing equipment
- Can be fabricated with no initial re-tooling or new patterns required - fewer parts from common materials
- Use existing control for conventional high NO_x burners
- Flame is not in contact with burner tip
  - No thermal stresses to cause metal fatigue
- Lower operational cost, and greater ease of operation, thanks to simpler combustion process

LSB Tested in Commercial Watertube & Firetube Boilers with External FGR

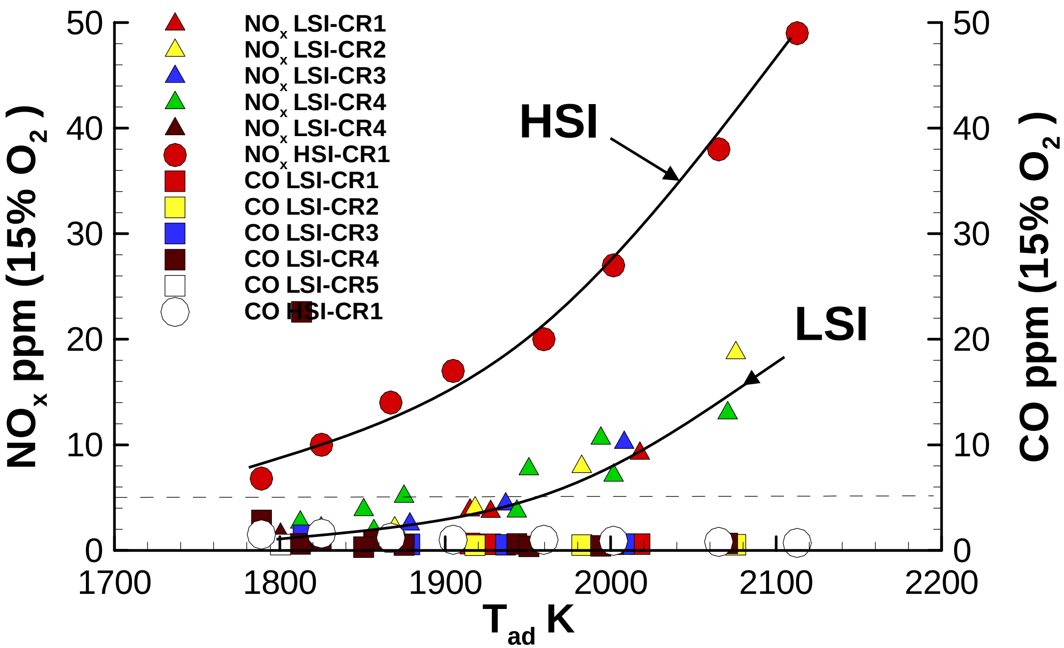
LSB Operating points for < 9 & < 5 ppm NO_x





- Use blower and controls for the commercial boiler
- Demonstrated low NO_x at partial load
- In-chamber flow pattern alters NO_x formation
- LSB shows good promise for improving system efficiency

Low-Swirl Flame Stabilization Concept Verified for Gas Turbines



- **Low-swirl injectors built from existing hardware**
  - **fully compatible with current engines, very low add-on cost**
- **Rig-tested at full load conditions (T < 700F, P < 15 atm)**
  - **Flame withstands large swing in inlet conditions**
  - **LSI does not encounter oscillations**
  - **Emissions not sensitive to degree of non-premixedness**
- **Lowest emissions match those of catalytic combustors**
  - **non-catalytic method does not require shorter cycle time**

High Swirl vs. Low Swirl for Flame Stabilization

	High Swirl	Low Swirl
Principle	Vortex traps hot products and continuously ignites fresh mixtures	Flame propagates freely in a turbulent divergent flow with no recirculation
Flame/ turbulence interaction	Flame developing in high shear region leads to flame fragmentation and occasional detachment	Flame developing in isotropic turbulence with low shear stresses is less prone to fragmentation
Instability	Characteristic frequencies associated with recirculating vortex	No characteristic frequency due to absence of recirculation

Conclusions

- **Simple scaling rules developed for LSB**
  - **Functionality of scaling rules verified by successful development of burner products and prototypes from 1 to 30 MMBtu/hr**
- **PIV experiments provided explanation for LSB's robust performance**
  - **Found LSB generates self-similar flowfield**
    - **Flow divergence constant in non-dimensional space**
    - **No flame shift due to linear scaling of turbulence intensity and flame speed, and weak dependence on fuel/air ratio**
  - **Knowledge essential for identifying, prioritizing and resolving operational issues**
    - **Placement of flame ignitor**
    - **Protocol to maintain flame stability during load change**
    - **Premixing requirement**
    - **Conditioning of flow supplied to the burner**
    - **Prevent the formation of downstream recirculation**

Outlooks

- **Promote low-swirl flame stabilization method as a new combustion platform**
- **Burners**
  - **Process heat – with Maxon: lean/lean staging, internal FGR and preheat**
  - **Boilers & petroleum refining – continue testing with potential development and commercialization partners**
- **Turbines**
  - **Mid-size turbines – begin engine test in Winter 2004**
  - **Micro & utility turbines – seeking research & development partnerships**
  - **IGCC turbines – seeking research and development partnerships**
- **Enabling technologies**
  - **Partial reforming – seeking demonstration partners**
  - **Alternate fuels – demonstrated firing with H_2, HC/H_2, biomass & low-Btu fuels. Seeking R&D opportunities**
  - **Prevaporized premixed liquid fuels – Exploring R&D partnerships**
  - **Combine heat & power generation – LSB+LSI, burning of vitiated air:**